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A Recent Electronic Control Circuit to a Throttle Device

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Abstract: The main objective of this paper was to conceive a new electronic control circuit to the throttle device. The throttle mechanical actuator is the most important part in an automotive gasoline engine. Among the different control strategies recently reported, an easy to implement control scheme is an open research topic in the analog electronic engineering field. Hence, we propose using the nonlinear dwell switching control theory for an analog electronic control unit, to manipulate an automotive throttle plate. Due to the switching mechanism commuting between a stable and an unstable controllers, the resultant closed-loop system is robust enough to the control objective. This fact is experimentally evidenced. The proposed electronic controller uses operational amplifiers along with an Arduino unit. This unit is just employed to generate the related switching signal that can be replaced by using, for instance, the timer IC555. Thus, this study is a contribution on design and realization of an electronic control circuit to the throttle device.

Keywords: electronic control design; throttle device; switched system

1. Introduction

There are many engineering systems involving sequence on time switching actions, or a switching-rule, among a finite set of given controllers. Hence, the resultant closed-loop system is a kind of a switched system [1–4]. Essentially, a switched system may be interpreted as a hybrid dynamical system where the switching-rule mandates the continuous-time subsystem to be activated from a set of stated subsystems. This set of subsystems may contain the resultant closed-loop schemes obtained by invoking a set of granted controllers. Some examples of hybrid systems include: robotics, flexible manufacturing, power conversion, and automotive transmission systems [2,5]. For a historical mathematical review on this topic, see [6] and the references therein. On the other hand, a special case of a switched system consists of both Hurwitz stable and unstable subsystems [1,3]. Therefore, for instance, a linear closed-loop and switched system can be represented by [1,3]:

$$\dot{x}(t) = A_{\sigma(t)}x(t), \quad x(t_0) = x_0 \quad (1)$$

where $x(t) \in R^n$ is the state of the system; t_0 and x_0 are its initial time and initial state, respectively. The switching signal $\sigma(t) : [t_0, \infty) \rightarrow I_N = \{1, 2, \dots, N\}$ is a piece-wise constant function of time and the switching subsystems $A_{\sigma(t)} : [t_0, \infty) \rightarrow \{A_1, A_2, \dots, A_N\}$. It is assumed that each A_i ($i \in I_N$) is a constant matrix of appropriate dimensions, and $N > 1$ is the number of subsystems to switch. Additionally, a given positive constant τ_d , named the dwell time, basically represents the smallest time between consecutive switching commands. Hence, by notation, $S[\tau_d]$ denotes the set of all switching signals satisfying the dwell time τ_d restriction. In [3], it is demonstrated that if the number of switching activities are enough big and the total activation time of the unstable subsystems is relatively small with respect to the total activation time of the stable subsystems, then the switched system (Equation (1)) is asymptotically stable under any set $S[\tau_d]$.

On the other hand, the throttle device is the main mechanical actuator in gasoline engine vehicles [7–10]. Moreover, this device may emulate other actuator schemes like the pitch mechanism in wind turbines [11]. Moreover, in the last decade, many control techniques to this mechanical device have been proposed. These include: adaptive control, neuronal networks, sliding mode control, control base model, learning PID control design, and design in a discrete-time domain [12–17], just to name a few. It is well-known that the throttle device is a non-linear system. Hence, it is difficult to control and capture all its dynamics and strong, nonlinear behavior by just using standard linear control framework.

Therefore, the main objective of this paper was to create a simple electronic circuit design to manipulate the throttle device, based on the dwell time switching control theory. This design is restricted to the analog electronic circuit field. This approach is an option, for instance, for the design declared in [11]. To support our approach, we deliver experimental results too. We used a throttle presented, for instance, in [11].

Finally, the rest of this document is structured as follows. Section 2 exhibits the theoretical account of the dwell time switching control mechanism (previously introduced) to obtain the basic rules to be followed on our control circuit design. Then, the experimental platform description and the related results are shown in Section 3. This includes materials and discussions on the obtained results. Finally, in Section 4, a brief conclusion is written.

2. Theoretical Framework of the Electronic Control Circuit Design for the Mechanical Throttle System and the Main Control Problem Statement

A throttle device basically consists of a DC motor to drive its throttle plate, a gear box, and a nonlinear restoring spring system. Additionally, it has a throttle plate angular position sensor via a linear potentiometer. Figure 1 shows a photo of the throttle actuator used as described, for instance, in [8,10,11]. Figure 1 gives a schematic point of view of this mechanical body too. Additionally, Figure 2 describes our controller approach. In this figure, two controllers are manifested: $u(t) = \{K_1 e(t), K_2 e(t)\}$, where $e(t) = x(t) - x_{ref}$, $x(t)$ being the throttle plate angular position and x_{ref} the reference command signal that may be a piece-wise constant function. According to [11], a simple throttle model for the control design stage can be captured by:

$$\ddot{x}(t) = -a_1 \dot{x}(t) + a_2 u(t), \quad (2)$$

where a_1 and a_2 are constant positive system parameters. This model, obviously, ignores many nonlinear terms of a real throttle device. However, if the controller is enough robust, these non-linearities will be attenuated by the controller itself [11]. For control design, x_{ref} is assumed constant. Therefore, the closed-loop system is expressed by:

$$\ddot{e}(t) + a_1 \dot{e}(t) - a_2 u(t) = 0, \quad u(t) = \{K_1 e(t), K_2 e(t)\}. \quad (3)$$

In the above system, we assume that $K_1 > 0$ and $K_2 < 0$ are the constant controller gains. These parameters are set such that for K_1 the closed-loop system is unstable and for K_2 is stable in the classical sense of linear control theory. Therefore, the only missing thing is the design of the dwell time switching mechanism such that the closed-loop system be stable (see Figure 2). As it was mentioned in the introduction section, and essentially to our scenario, if the switching number is enough big and the total activation time of the unstable controller is relatively small with respect to the total activation time of the stable controller, then the given closed-loop switched system will be stable under any set $S[\tau_d]$. See [3]. Hence, a possible switching signal can be described as a pulse-width modulation (PWM) signal; see Figure 3. Therefore, according to the previous statements, there exists a period of this signal with time activation to the unstable controller, T_{ON} , and a time activation for the stable control T_{OFF} satisfying our requirements for stability. By our notation, this T_{OFF} on the unstable controller means the time activation to the stable controller. This kind of signal is in fact a PWM one with a fixed duty

cycle. Moreover, and from the electronic point of view, this PWM signal is relatively easy to realize by using, for instance, the well known timer IC555, or by employing an Arduino board, among other options, of course. We decided to employ an Arduino board for its simplicity. Finally, the closed-loop system (Equation (3)) can be stated in the format shown in Equation (1):

$$\frac{d}{dt} \begin{bmatrix} e(t) \\ \dot{e}(t) \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ K_i a_2 & -a_1 \end{pmatrix} \begin{bmatrix} e(t) \\ \dot{e}(t) \end{bmatrix}, \quad K_i \in \{K_1, K_2\}. \quad (4)$$

From the above system, it is simple to obtain the related matrix A_i ; that is: $A_i = \{A_1, A_2\}$ for $i = \{1, 2\}$, yielding:

$$A_1 = \begin{pmatrix} 0 & 1 \\ K_1 a_2 & -a_1 \end{pmatrix}, \quad (5)$$

and

$$A_2 = \begin{pmatrix} 0 & 1 \\ K_2 a_2 & -a_1 \end{pmatrix}. \quad (6)$$

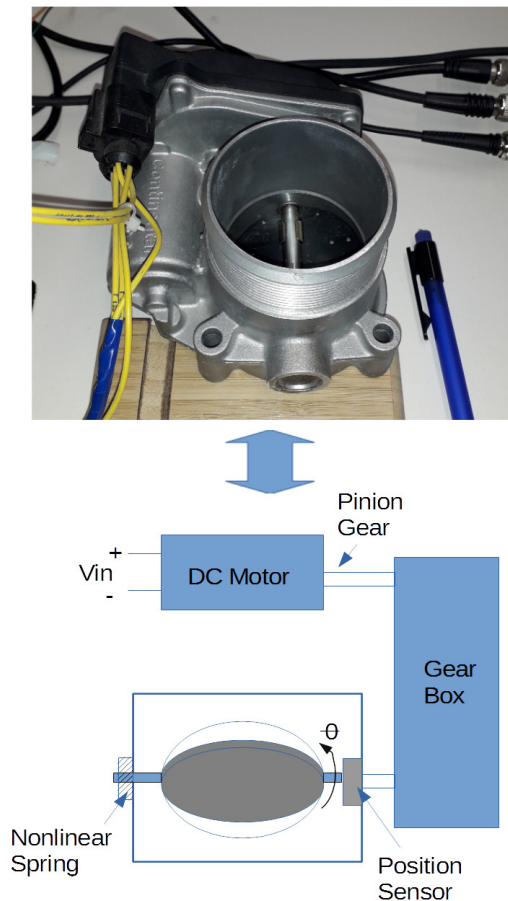


Figure 1. Top: A photo of our throttle device. Bottom: A throttle actuator diagram. V_{in} would be the control signal $u(t)$.

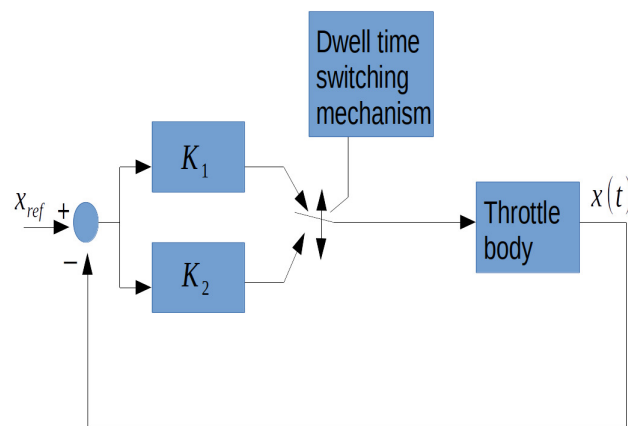


Figure 2. The proposed closed-loop control system.

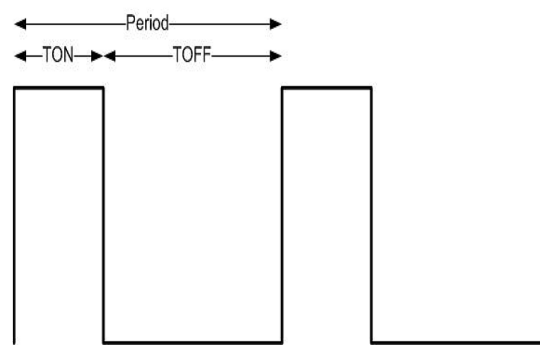


Figure 3. A dwell-switching signal which can be viewed as a pulse-width modulation (PWM) indicator.

Remarks on the Mathematical Model of the Throttle Mechanism

From the mathematical point of view, the throttle device has a complete non-linear model to primarily capture [18]:

- The throttle mechanical dynamic friction.
- The gearbox non-linearity disturbance.
- The complex return spring torque and non-linear behavior.

In [18], for instance, by using model simplification though bounding some terms, the throttle device model is notoriously simplified. See [19] too. Moreover, linear models of a throttle system have been employed, for instance, in [20]. Hence, the previous evidence motivates to use a linear system model in order to obtain a simple controller able to face the ignored non-linear terms in the control design stage.

3. Electronic Control Circuit Design, Experimental Results, and Discussions

Our electronic control circuit design is based on the overall schematic system illustrated in Figure 2. Therefore, an analog electronic circuit used to produce the proposed error signal, and then supply it to the switching controller, is shown in Figure 4. This circuit is straightforward to follow. The outgoing signal at A is sent to the circuit illustrated in Figure 5. See Figure 6 too. Once again, in this circuit, we use the LM741 operational amplifier and $C_s = 22$ pF. What is more, in this experimental development, the related PWM signal was produced by using a modulating index of 86.27% and obtained by

invoking the Arduino's command: `analogWrite(5220)`. Furthermore, the PWM signal supplied by the Arduino Uno at its pin 5 has a base frequency of 976.56 Hz, which is considered high enough for our main intention of controlling the throttle body. In order to satisfy the switching rule previously stated, the duty cycle of this PWM signal was experimentally varied until we noted the desired result. Additionally, Figures 7 and 8 display the experimental outcomes by manually manipulating the pedal emulator potentiometer (blue line) and observing the throttle angle response—shown in red. To recall, from [11], this throttle mechanism has a mechanical angular plate ranging from 14 degrees to almost 90 degrees. Then, the throttle plate angular sensor delivers a linear voltage from 2.0 to 4.6 volts, respectively. In our experiments, we used the PicoScope 2000 Series data acquisition card to evidence the previously cited results. In these figures, the vertical and horizontal scales are clearly marked. The experiments were carried out in a similar fashion to those in [7].

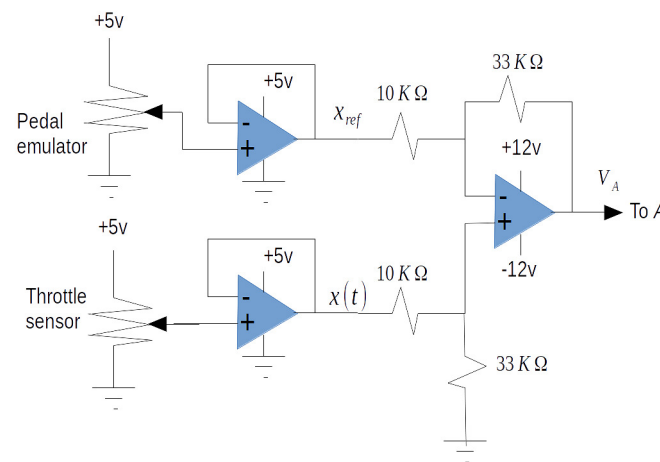


Figure 4. Analog electronic circuit: the error signal processing unit. Its response is then sent to the circuit in Figure 5. The operational amplifiers employed are inside the LM741 integrated circuit. Therefore, we obtain $e(t) = V_A = 33(x(t) - x_{ref})$.

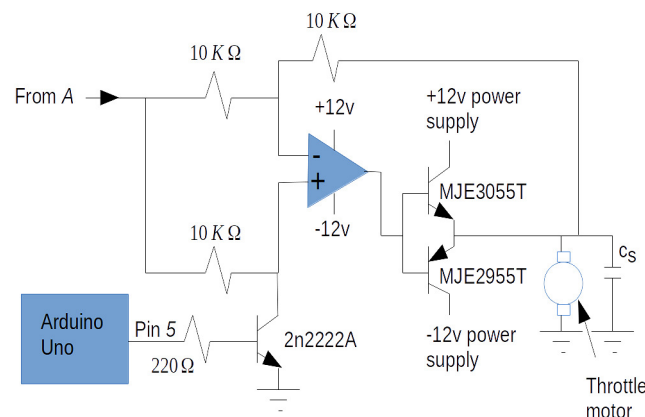


Figure 5. The electronic circuit to the switching mechanism unit. It receives information from the circuit in Figure 4. From this diagram, $\{K_1, K_2\} = \{3.3, -3.3\}$. The operational amplifiers employed are in the LM741 integrated circuit too. From this circuit, the 2N2222A npn-transistor is employed to switch between the inverting and non-inverting op-amp actions.

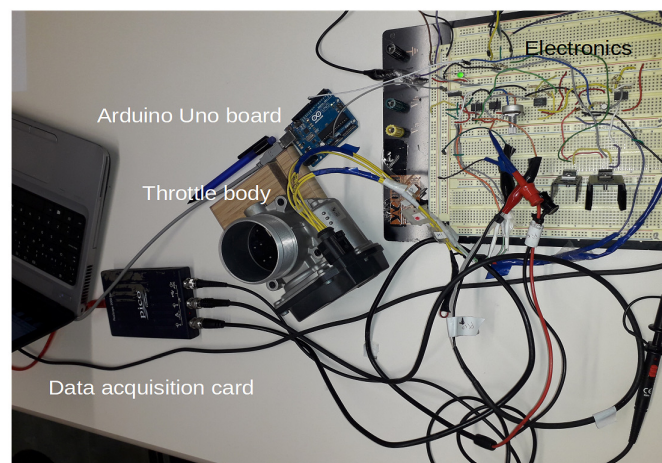


Figure 6. A photograph of the overall experimental platform.

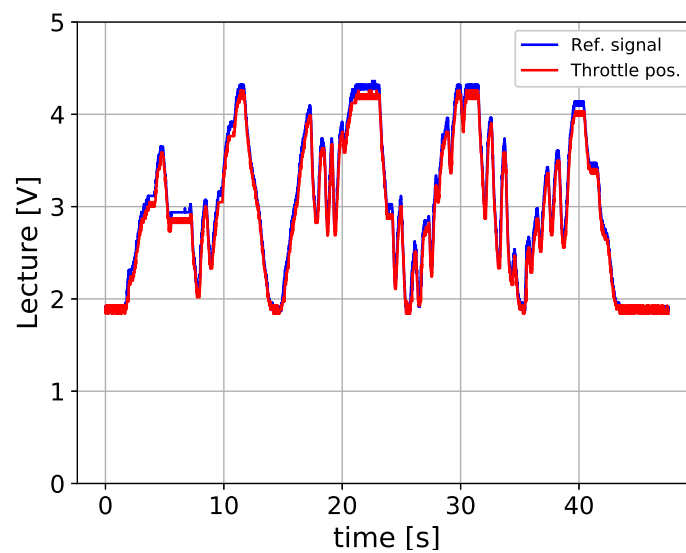


Figure 7. The throttle valve position follows the reference signal induced by the pedal emulator potentiometer.

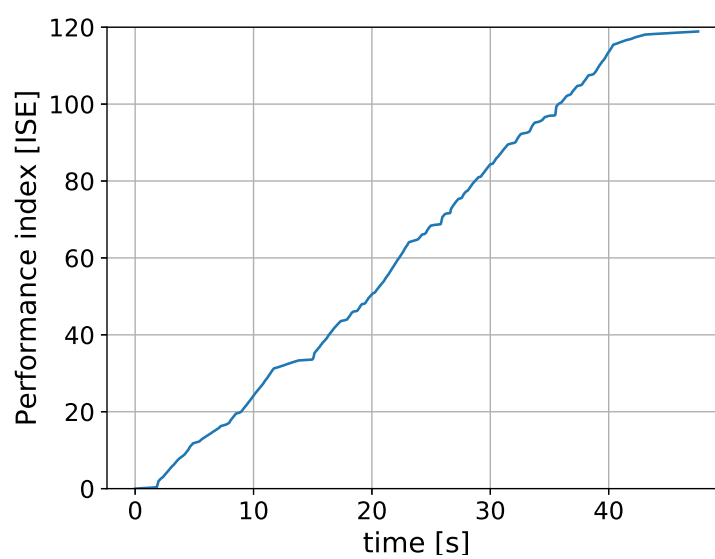


Figure 8. The ISE performance index obtained from the data in Figure 7.

As a comparison issue, and taking into account the experimental throttle design detailed in [7], we can stated the following:

- Our control approach is well-situated for electronic realization.
- Our control design does not use a dense data flow algorithm. For instance, in [7], its basic genetic algorithm (GA) requires a fitness calculation and selecting some GA individual objects.
- Our control structure has fewer control parameters to tune. For instance, in [7], there are 14 parameters to adjust.
- In [7], the next performance index on the tracking error during the experiment-time action can be read as:

$$J = \sup_{t_0 \leq t \leq T_s} [e(t)] = 0.05 \text{ Rad.}$$

However, in other experiments realized in [7], this error was about 0.095 Rad. In our case, we have:

$$J = \sup_{t_0 \leq t \leq T_s} [e(t)] = 0.13 \text{ Rad.}$$

The above number could be a disadvantage of our control design. However, a human outer-control loop exists in real automotive control driving to overcome this disadvantage.

To complete our experimental presentation, a video link is located at <https://youtu.be/zIo8XtT0gbY>. To evidence that our controller's performance is sensitive to both the base frequency and the PWM duty cycle, Figures 9–11 show the observed-data when the PWM base frequency is 7812.50 Hz. Figure 9 corresponds to the case when the modulation index of the PWM is 19.6%, and Figure 10 for the event of 98.03%. To recall, the reference command is introduced by manipulating a potentiometer. Hence, this signal is a kind of human-random signal. Table 1 resumes our experimental outcomes. From this Table, we can appreciate that the control performance can be improved by increasing the PWM frequency and by properly manipulating its duty-cycle. Finally, outcomes interesting that, from the experimental results, the tracking error is significantly reduced when the closed-loop system is operated with enough velocity on its reference command. This is also observed in the proposed controllers in [21,22]. Hence, we can arrive to the same conclusion: that the tracking error is reduced if the system is operated with enough velocity.

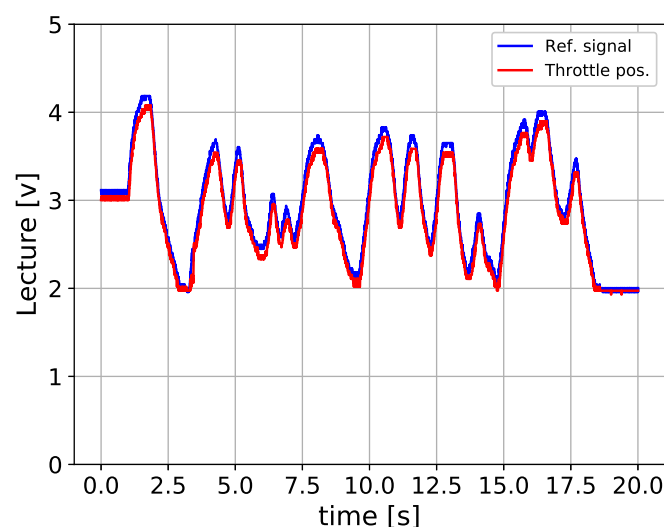


Figure 9. The throttle valve position following the reference signal induced by the pedal emulator potentiometer.

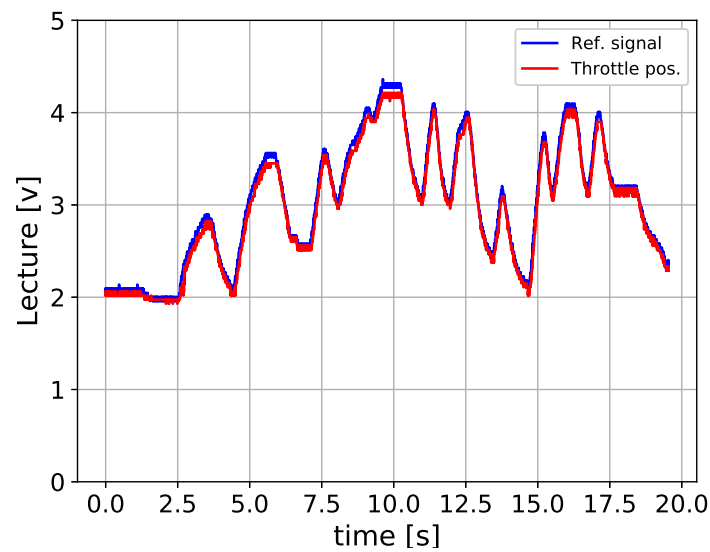


Figure 10. The throttle valve position follows the reference signal induced by the pedal emulator potentiometer.

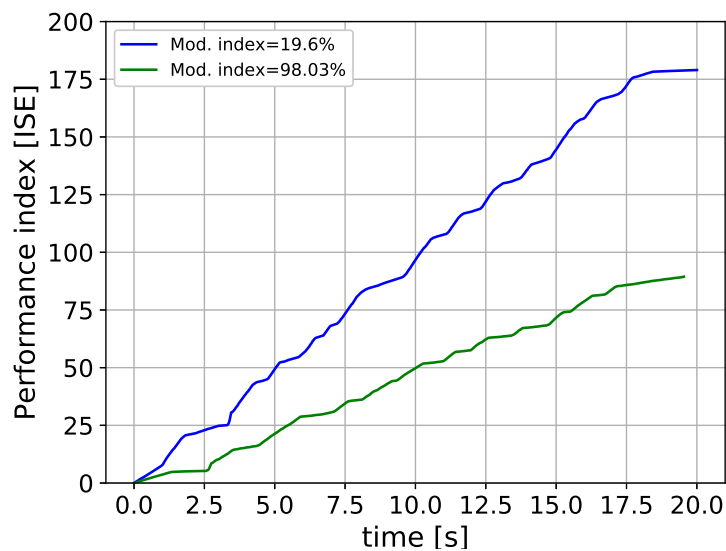


Figure 11. The ISE performance indexes incurred from the data in Figures 9 and 10, respectively.

Table 1. The remainder of the experimental results.

PWM Frequency [Hz]	PWM Duty Cycle [%]	ISE _{max}
976.56	86.27	119.5
7812.50	19.6	178.6
7812.50	98.03	88.8

4. Conclusions

To resume, this paper has proposed the design of a new nonlinear controller for the automotive throttle device by using an analog electronic circuit. This circuit was possible because of the theory employed on the switching dwell time control system. On the other hand, one important key is its cost, which is about 50 euros, including the Arduino Uno unit. Moreover, and from the academic engineering point of view, this electronic circuit would be useful for teaching electronics to the automatic control students, when applied to the challenger control topic, as is the controller of an automotive gasoline engine throttle body.

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